Statistics of GPS Satellite Links in the Presence of Equatorial Scintillation

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ABSTRACT**.** A network of Global Positioning System (GPS) single frequency (L1) receivers has been installed in Australia and South East Asia for the purpose of monitoring equatorial ionospheric scintillation during the current peak in solar cycle activity. We present preliminary results from the first two years of operation (1998 and 1999). Analysis of the performance of simultaneously active satellite links indicates that, even prior to solar maximum, the number of simultaneous links sometimes falls to near the minimum of 4 required for a navigation solution. We conclude that in the presence of equatorial scintillation, GPS performance can be marginal.

1. INTRODUCTION

The navigational performance of GPS receivers in the equatorial region has the potential to be compromised by amplitude and phase scintillations imposed on the satellite signals by the occurrence of ionospheric irregularities [1]. At equatorial latitudes, such irregularities reach a peak in occurrence after sunset and during periods of high solar cycle activity [2]. There is also a seasonal variation, with peaks in activity in the Australian/Asian longitude sector appearing around the equinoxes, in March and September. With the exception of the work of Fang and Liu [3], there has been a relative lack of statistical data on the occurrence of irregularities in this geographical region.

The formation of the irregularities is broadly understood and is attributed to the Rayleigh-Taylor Instability [4] in which a perturbation, forming on the bottom-side of the ionospheric F2 layer, is amplified at the magnetic dip equator to produce an upward moving bubble of depleted ionisation. This soon breaks down into a spectrum of smaller irregularities which map down magnetic field lines towards the north and south Appleton anomaly crests at around 12 to 15 degrees magnetic latitude [5].

The resulting irregularities are most intense at the anomaly crests and are characterized by a spectrum of scale sizes which constitute a random diffraction screen to any signals passing through it. Consequently, scintillations in amplitude and phase may be imposed on the signals from orbiting satellites such as those of the GPS with the result that the signal tracking loops of a navigation receiver, depending on its design, may experience difficulty in maintaining lock on the signal. Since a successful GPS navigation solution requires the maintenance of links to at least four satellites, the loss of a sufficiently high number of satellite links through scintillation has the potential to adversely affect system performance.

2. RECEIVER NETWORK CONFIGURATION

The locations of GPS stations currently operating in the network is shown in Figure 1. The stations are located at Marak Parak (Malaysia), Parepare(Indonesia), Pontianak (Indonesia),

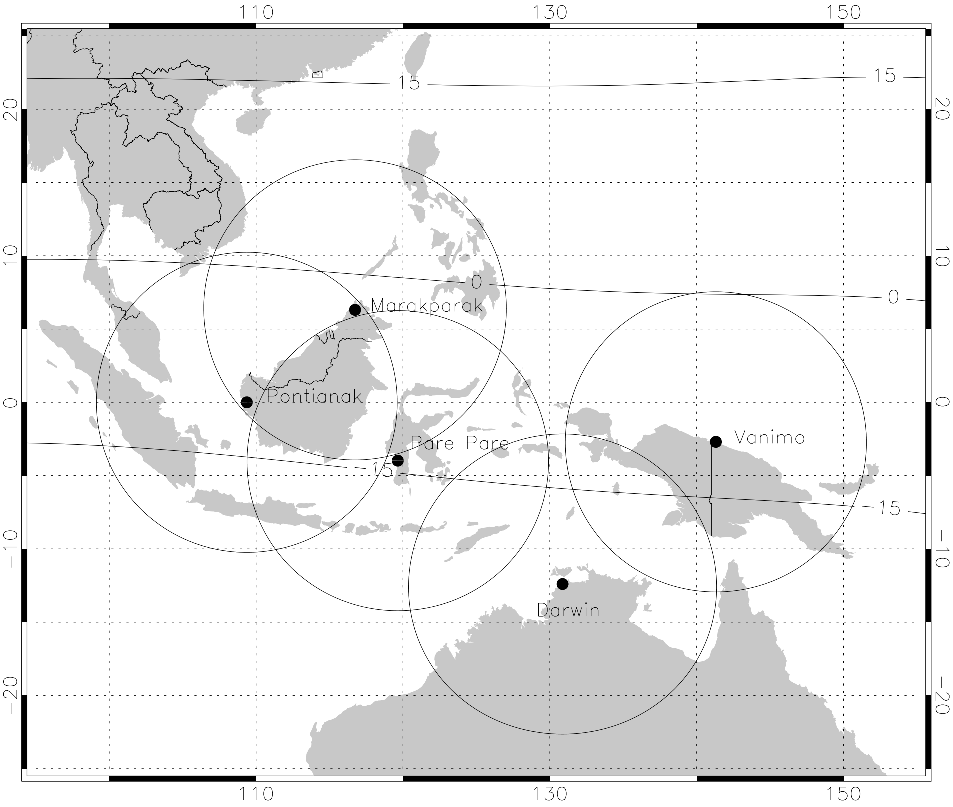

Figure 1. Locations of GPS receiver network stations with coverage circles of radius 1140 km (elevation 15°, altitude 400 km), magnetic dip equator and lines of magnetic latitude for 15° north and south.

Darwin (Australia) and Vanimo (Papua NewGuinea). Details of the station locations are shown in Table 1. Marak Parak may be considered a magnetic equator site, Pontianak, Parepare and Vanimo lie more or less under the southern anomaly crest and Darwin is pole-ward of the anomaly. Thus the network monitors a wide area, covering about 50 degrees of longitude and 35 degrees of latitude, mostly south of the magnetic equator. Instrumentation at each station includes an Ionospheric Scintillation Monitor (ISM).

Table 1 Station locations (in degrees)

Station	Geog lat	Geog long	IGRF	(1998)
			Geomag lat	Dip
Parepare	-3.98	119.65	-12.6	-26.2
Pontianak	0.00	109.37	-8.4	-18.8
Marak Parak	+6.31	116.74	-1.3	-3.8
Darwin	-12.4	130.87	-21.9	-40.5
Vanimo	-2.4	141.2	-10.8	-21.6

3. EQUIPMENT

The five ISMs are provided by Air Force Research Laboratory, Hanscom, Massachusetts. The design is described in detail by Van Dierendonck et al [6,7]. It comprises a NovAtel 11-channel single frequency (L1=1.57542 GHz) C/A (Coarse Acquisition) code receiver fitted with an oven-controlled crystal oscillator for low phase noise performance. This narrow correlator receiver has a relatively wide phase-lock-loop noise bandwidth of 15 Hz, and should track through severe phase scintillation. The received signals are sampled at a rate of 50 Hz under computer control which, depending on the selected operating mode, provides either a block of raw 50 Hz data logged every second or processed data every minute. Processed data are collected on all 11 channels, but for the raw data mode, the much greater volume of data limits operation to a maximum of 3 available channels. However, we rarely use this mode of operation, processed data collection being the norm. Data are saved to an external 1 Gbyte removable disk which is changed at intervals of from 2 to 4 weeks for post-processing. When sufficient post-processed data are accumulated, they are archived and copied to a CD-ROM for distribution to project partners.

The ISM provides a number of processed scintillation parameters. Phase scintillation is monitored through the standard deviation σ_ϕ and the power spectral density of de-trended carrier phase from each satellite. For further analysis, we use the measured σ_ϕ averaged over a 60 second period. Amplitude scintillation is monitored through the S4 index, which is the normalised standard deviation of the de-trended received signal power. This parameter is made available both in raw form or as a corrected S4, for which the effects of ambient noise have been removed. We work with the corrected value of S4 in subsequent analysis of our recorded data. In the absence of scintillation and multipath, corrected S4 values should lie below 0.05. In scintillation conditions, values from 0.05 up to 1.0 may be obtained. But we note that measurement of S4 using this system becomes subject to some uncertainty due to stressing of the receiver tracking loops at the highest scintillation levels, when S4 values exceed about 0.7. Data gathering for the ISMs commenced at Parepare, Pontianak and Marak Parak in December 1997, at Darwin in June 1998 and at Vanimo in August 1999.

4. SUMMARY RESULTS

Figure 2 shows, in summary (or "quick-look") form, the corrected S4 data from the Vanimo station throughout the day of 20 September 1999.

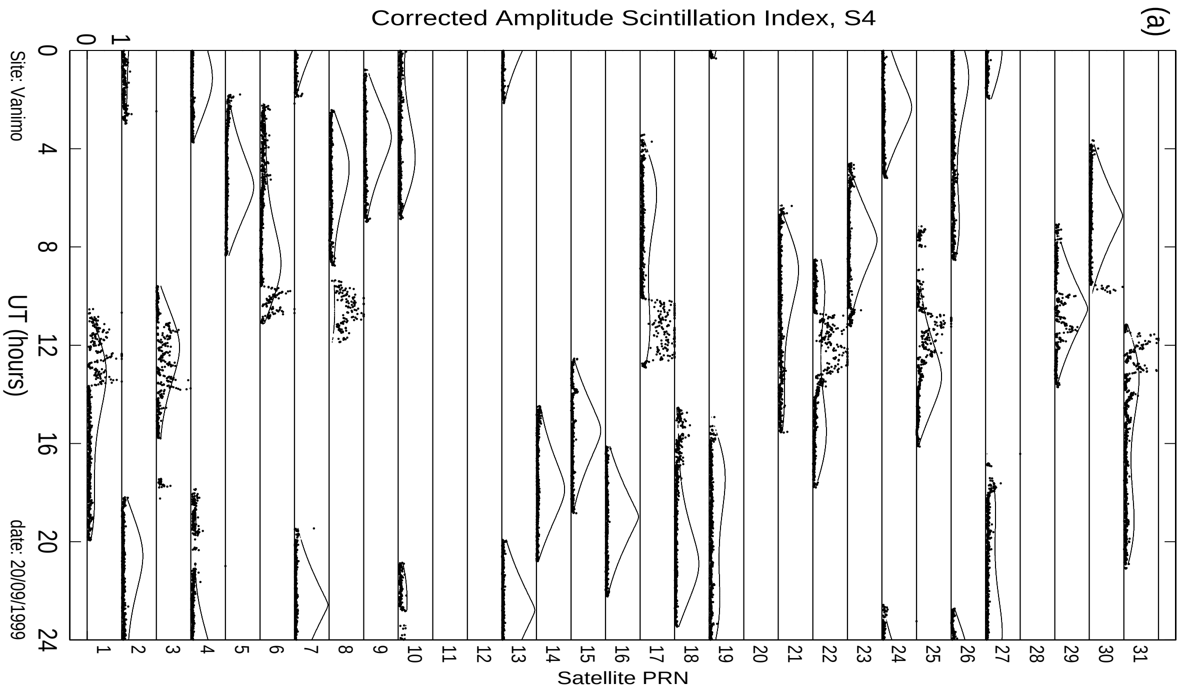

Figure 2. Summary plot of amplitude scintillation index S4 for each satellite (PRN) at the Vanimo station on 20 September 1999, with elevation angles given by the continuous curves.

The data show that this was a particularly active night with a large number of satellites experiencing scintillation. The monthly average sunspot number for September 1999 was 70.9, and the predicted annual average sunspot number was 118.4, compared with about 160 predicted for when the maximum is reached between 2000 and 2002. Each satellite is identified by a unique PRN, or pseudo-random noise code number. The scintillation indices from individual satellites are stacked vertically from PRN1 (the bottom plot) to PRN31 (the upper-most plot). For each satellite, plots are functions of Universal Time (UT) with corrected S4 in the range from 0 to 1. The continuous curves plot satellite elevation angle in the range 0 to 90 degrees. Enhanced scintillation activity at low elevation is usually attributed to multi-path propagation and should be ignored. During daylight hours from 20UT to about 10UT (approximately 06 to 20 local time (LT)), conditions as expected are very quiet with no indication of signal scintillation. However, at about 10UT (2 hours post sunset), scintillation commences on most satellites in view and persists more or less for the next 4 hours (until about midnight LT). This behaviour is rather common for equinoctial nights when scintillation occurs, except during solar minimum years when there would be considerably less activity. Even more intense activity is to be expected as we reach sunspot maximum. Presentation and discussion of σ_ϕ data is beyond the scope of this paper.

5. REGIONAL CORRELATION OF SCINTILLATION ACTIVITY

On those nights when scintillation occurs, it is of interest to investigate the size of the region affected. We have therefore applied a given S4 threshold to the data from pairs of stations in our network and calculated the percentage of nights when at least one GPS link at *both* stations was (a) below and (b) above this threshold level of activity. The sum of (a) and (b) is therefore the percentage of nights when the same behaviour, relative to the selected threshold, was observed to be occurring at both sites, and is a measure of the correlation between S4 values at the two stations. We have carried out this analysis for the period September-October 1999 using data from Marak Parak (magnetic equator), Parepare, Pontianak and Vanimo (anomaly crest). Data from Darwin are too incomplete to be used in the analysis at this time. Station great circle separations vary between 1030 km (Pontianak-Marak Parak) and 3540 km (Pontianak-Vanimo). The results for a threshold of S4>0.6 are given in Table 2.

Table 2 : Regional Pair-wise Correlation of Nightly Scintillation Behaviour
(Sep/Oct 99 and S4>0.6)

Station	Parepare	Pontianak	Vanimo
Marak Parak	75%	76%	71%
Parepare	-	70%	69%
Pontianak	-	-	76%

Table 2 shows that if, on a given night, scintillation occurs above a level of S4=0.6 on at least one link at any one station in the network, then the probability is between about 70% and 80% that the other stations will have at least one link which also records scintillation above S4=0.6 on that night. The high correlations suggest that on scintillation nights, favourable conditions for the formation of equatorial irregularities extend along the equator throughout the network, covering a longitude interval of at least 50 degrees. It is clear that our stations lie wholly within this local correlation region and in order to define the regional boundaries, additional scintillation stations need to be established to the west and to the east. The correlation distance in latitude is determined by the north and south anomaly crests and is not an issue, except possibly in so far as the latitudes of the crests may vary somewhat with sunspot number.

6. EFFECT OF SCINTILLATION ON MULTIPLE GPS SATELLITE LINKS

Links to at least 4 satellites are required to be maintained in order for a receiver to provide an unaided navigation solution, since the receiver must solve for 4 "unknowns", namely the user's location in the 3 spatial dimensions, plus the user's clock bias with respect to system time [8]. If the number of simultaneous links falls below 4, the system will fail, at least until the necessary links are re-acquired. The consequences of such a failure could be disastrous for a system which is critically dependent on GPS for its navigation. So it is of considerable interest as we approach sunspot maximum to investigate the likelihood of such a failure resulting from scintillation-induced loss of lock in a GPS receiver.

We have carried out such an investigation using Vanimo ISM data from September 1999, applying an elevation mask of 15 degrees, and S4 threshold levels of 0.3 and 0.6 respectively, by computing the number of links (or satellites) for which each S4 threshold is simultaneously exceeded for each minute of the day.

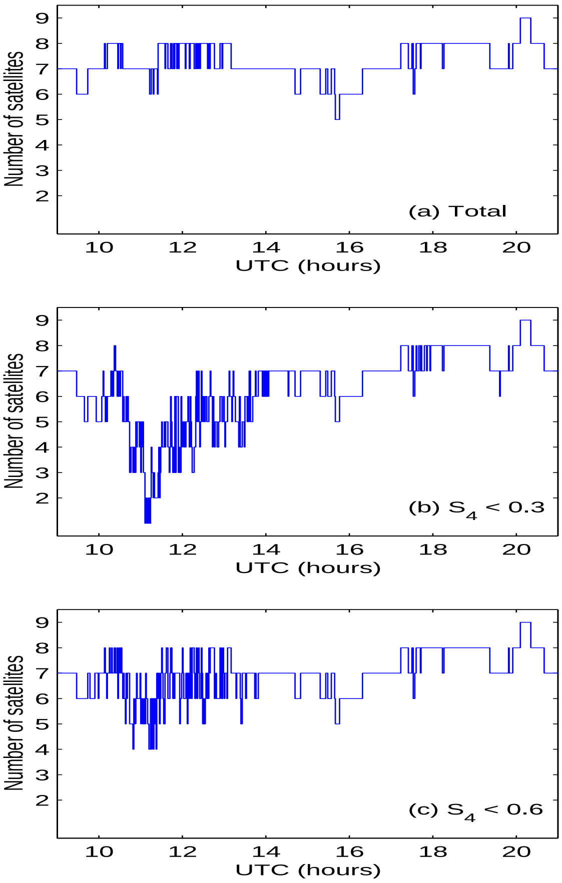

Figure 3. "Surviving" links as a function of time during 20 September: (a) the total number of available links at one minute intervals, (b) the number of links remaining after subtracting those affected above a threshold of S4=0.3, and (c) the number remaining after subtracting those affected above S4=0.6.

Figure 3 examines the record of "surviving" links at Vanimo for the single day of 20 September 1999 from 09UT to 21UT (approximately 19LT to 07LT), by comparing 3 histograms, (a) the total number of satellite links present for each one minute interval throughout the day, (b) the number of links remaining below the weak scintillation threshold (S4 < 0.3), and (c) the number remaining below the moderate scintillation threshold (S4 < 0.6). It can be seen from histogram (a) that at Vanimo the total number of simultaneously acquired links varied between 5 and 9. In weak scintillation conditions (histogram (b)), the number of links remaining below the S4 threshold fell briefly to as low as 1 at 11:15UT. Of more concern, there was a cluster of occasions when only 4 links remained below the moderate scintillation threshold (histogram (c)). We are unable to say what maximum value of S4 above 0.7 was reached during this event, but we do know that system integrity was maintained and so lock was held on at least 4 links. Nevertheless, it is clear that system performance approached marginal limits.

It may be argued that our use of a 15 degree elevation mask in order to avoid multi-path contamination could over-estimate the likely system degradation, since other GPS users may be able to utilise additional links at lower elevations. However it should also be appreciated that other GPS users may not have the advantage of stationary receivers and a controlled environment; they may be subject to platform dynamics and signal path obscuration due to terrain, buildings and foliage, depending on how and where the receiver is being used at any time. GPS users operating in a marginal environment are likely to be more susceptible to scintillation than is our network.

We conclude that for these Vanimo data taken at the September 1999 equinox, just prior to sunspot maximum, there was at least one night (20 September) when GPS system performance was on the verge of being compromised by scintillation. The strong regional correlation described in Section 5 above indicates that similar behaviour could be expected from our other sites. We have not considered the performance of Differential GPS, which is likely to be more susceptible than individual receivers. We also caution that at the time of these measurements the peak in solar activity still had not been reached. We plan to continue monitoring multiple link performance throughout the sunspot maximum period, and to extend the analysis to our other stations.

7. CONCLUSION

The GPS receiver network described above will provide crucial data on equatorial scintillation and TEC during the maximum in solar cycle activity which is due in 2000-2002. In this paper, we have reported initial results obtained in the lead-up to solar maximum (1998-1999) which show that scintillation occurrence is highly correlated over the receiver network and that the integrity of simultaneous multiple GPS satellite links during episodes of scintillation can approach a marginal condition, even before sunspot maximum has been reached. To the best of our knowledge, such information is not yet included in any model which would be a vital tool in order to properly evaluate GPS navigation performance.

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